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Danish Atomic Energy Commission
Research Establishment Risø

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by D. Dimock, K. Jensen, V. O. Jensen, L. W. Jørgensen,
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Pellet Acceleration

Studies Relating to the Refuelling of a Steady-state Fusion Reactor

by

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Abstract

Several methods for refuelling a steady state-fusion reactor have been proposed, and the pellet method seems advantageous if the pellet can be accelerated to the necessary velocity.

A study group was formed to analyze this acceleration problem. Two pellet velocity values were considered: 10^4 m/s and 300 m/s. A pellet velocity of 10^4 m/s may be suitable in the case of a reactor, whereas 300 m/s is believed to be a reasonable velocity at which to perform realistic ablation experiments in the near future. A pneumatic acceleration method was found promising. The pressure is either supplied separately or by evaporation of a part of the pellet. In the latter case, a spark behind the pellet should provide the evaporation and the necessary heating of the driving gas. A preliminary test at room temperature with pellets made of beeswax (the density being ten times that of solid hydrogen, and the plastic properties similar to those of solid hydrogen) resulted in a pellet velocity of 100 m/s at a modest value of the energy supplied to the spark.

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1. INTRODUCTION

Steady-state fusion reactors of the future may perhaps be refuelled by the injection of high velocity DT pellets. The feasibility of this scheme is very dependent upon the velocity to which it is possible to accelerate a hydrogen pellet, and thus we undertook an analysis of various acceleration methods.

The size of the pellets required for the purpose is no well-defined quantity, but linear dimensions in the range of 0.1-10 mm may be assumed. The smaller the pellet, the greater the velocity needed but, on the other hand, the maximum size is restricted by the tolerable local density and temperature perturbation inside the fusion plasma. The velocity to which a pellet of a given size must be accelerated depends on the parameters of the reactor and on the penetration properties of the pellet. The physical mechanisms dominating the interaction between a pellet and a plasma are unknown at present. Altogether it is difficult to give a reliable estimate of the velocity required, but from theoretical models of the interaction in question, a velocity of 10^4 m/s may be realistic.

In order to predict more precisely the relation between pellet-size and the necessary velocity, it seems essential to perform experiments at an intermediate pellet velocity. A reasonable velocity may be 300 m/s because a pellet having this velocity has a possibility of penetrating a typical present-day Tokamak plasma. This conclusion is based on figures in a theoretical work by Gralnack¹⁾. Therefore, the present report not only deals with the acceleration of a pellet to a velocity of 10^4 m/s, but also with methods of reaching the more urgently required value of 300 m/s.

SI units are used in this report.

2. PROPERTIES OF SOLID HYDROGEN

2.1. Mechanical Properties

The tensile strength of the pellet material can impose an upper limit on the acceleration of the pellet. The stress required to produce a permanent deformation - the yield strength - can lead to an even more conservative estimate. Table 1 gives values for the tensile strength at 4.2 K for various deformation rates (from ref. 2).

Table 1

Deformation rate sec ⁻¹	Tensile strength, σ N/m ²	Relative elongation, ϵ %	Hardening coefficient, $M \equiv \frac{d\sigma}{d\epsilon}$ N/m ²
4×10^{-5}	4.5×10^5	6	5.3×10^7
20	5.1	8	6.9
420	5.5	17	14.4

The yield strength, σ_y , was measured to approximately 10^5 N/m², and Young's modulus of elasticity E was found to be 2.9×10^5 N/m². Alternatively, σ_y could be estimated from measurements of the shear strength, τ , using the relation $\sigma_y \approx \sqrt{3}\tau$. Measurements of the shear strength have been reported³⁾, and a value $\tau = 16 \times 10^5$ N/m² is estimated at a pressure of 1 atm. Using this value, we obtained $\sigma_y \approx 28 \times 10^5$ N/m². The large difference between the two values of σ_y indicates the uncertainty of these parameters. The measurements of the shear strength appear to be the most difficult to perform and they are probably the least reliable because of a strong work-hardening of hydrogen. Furthermore, the value of the shear strength is obtained by extrapolation of a curve based on a few uncertain data.

The data reported here are valid for parahydrogen of 99.9% purity, but they can probably be applied to deuterium and tritium too.

2.2. Thermal Properties

The molar volume and the density for normal deuterium and for hydrogen (para and normal) are given at different temperatures in table 2.

The values given in table 2 are taken from references 4, 5, 6 and 7. The agreement between them is excellent. The triple point for normal hydrogen is 13.96 K, for normal deuterium it is 18.71 K, while the corresponding vapour pressures are 54.04 mm Hg and 128.5 mm Hg respectively⁵⁾.

The latent heat for normal hydrogen⁸⁾ is 117 J/mol at the melting point and 904 J/mol at the boiling point (20.4 K).

Table 2

K	Deuterium		Hydrogen	
	V m ³ /mole	ρ kg/m ³	V m ³ /mole	ρ kg/m ³
4.2	1.956 x 10 ⁻⁵	204	2.265 x 10 ⁻⁵	89.0
10	1.983		2.292	
14	2.012		2.326	86.7
16	2.026	197		

The heat capacity⁹⁾ for parahydrogen and normal deuterium is shown on fig. 1.

The thermal resistance for deuterium is shown on fig. 2¹⁰⁾.

3. ACCELERATION METHODS

The following methods of acceleration are discussed in greater or lesser detail:

1. Mechanical
2. Electromagnetic
3. Laser
4. Electrostatic
5. Pneumatic

3.1. Mechanical Acceleration

Due to the low values of the tensile strength of solid hydrogen reported in the previous section, mechanical acceleration was eliminated as a realistic possibility of accelerating pellets to either 300 m/s or 10⁴ m/s, since the solid hydrogen would have to be contained in a carrier that would have to be accelerated and then stopped again.

3.2. Electromagnetic Acceleration

A proposal for electromagnetic acceleration was made a few years ago by Chubb¹¹⁾. A pellet is placed in a conducting carrier that is driven through an induction tube. An acceleration length of 100 m was assumed. Any length much shorter than this is not tolerable because of melting of the

carrier by Joule heating. This implies an acceleration of $5 \times 10^5 \text{ m/s}^2$, which is acceptable.

A safety problem arises in connection with this method since the carrier would seriously damage the reactor if allowed to hit it. However, since the carrier flight path needs to be deflected in any case, part of the deflection apparatus could consist of a permanent magnet located so as to provide a fail-safe trajectory.

We have not considered this proposal in detail, especially not a design for a velocity of 300 m/s. In both cases the method seems difficult from a technical point of view.

3.3. Laser Acceleration

This possible acceleration method is based on the idea that a laser beam with a hollow intensity profile may create an ablation pressure sufficient to accelerate a pellet over a path length of the order of 1 cm within a time of about 1 μs . The reason for the short pulse duration and path length is that the ablated plasma would rapidly shield the back of the pellet from the laser, and heat conduction through the shielding layer would not be sufficiently fast to maintain the ablation pressure. On the other hand, it would be fast enough to evaporate the pellet.

Clearly, the method requires an acceleration value much higher than solid hydrogen is able to withstand.

3.4. Electrostatic Acceleration

The velocity v of a spherical pellet with radius r accelerated through a potential drop V can be expressed as

$$v = \sqrt{\frac{8\pi\epsilon_0 r^2 V E}{m}} = \sqrt{\frac{6\epsilon_0 V E}{\rho r}}, \quad (1)$$

where ϵ_0 is the permittivity of free space, E is the electric field at the surface of the pellet, m is the mass, and ρ is the pellet material density.

This method necessitates a high electric field at the surface of the pellet and a high accelerating voltage to obtain a velocity of the size required. A pellet charged positively may sustain a field at the pellet surface of the order of $10^8 \text{ V/m}^{(12)}$ before disruption. For a negatively charged pellet, electron field emission occurs at a field of a few times $10^9 \text{ V/m}^{(12)}$. (Interesting pioneering work on this subject was done by Rayleigh⁽¹³⁾).

It is also necessary to consider the mechanical stress introduced into a charged sphere. The stress P is given by

$$P = \frac{1}{2} \epsilon_0 E^2. \quad (2)$$

Using $5 \times 10^5 \text{ N/m}^2$ for the tensile strength, from table 1, we obtain a value of $3.4 \times 10^8 \text{ V/m}$ for the maximum electric field. Figure 3 plots the velocity of a hydrogen pellet from (1) versus the accelerating voltage for this value of the electric field. We have used $\rho = 88 \text{ kg/m}^3$ from table 2.

From the figure it is seen that, for example, to reach the modest velocity value of 300 m/s a pellet with radius 1 mm requires an accelerating voltage of $4.5 \times 10^5 \text{ V}$.

Appendix 1 considers the possibility of coating a hydrogen pellet with a stronger material, e.g. beryllium, which is also a light material. The increase in possible pellet velocity resulting from coating a hydrogen pellet with a beryllium shell is also calculated in this appendix. We find a maximum increase in the velocity of $\sim 50\%$.

Even if a great improvement in velocity could be obtained by coating a pellet, the amount of impurities introduced (at least into the outer layers of the plasma) could prohibit the scheme.

3.5. Pneumatic Acceleration

An appreciable pellet velocity might be reached by applying hydrogen gas at high pressure to the rear of a cylindrical hydrogen pellet. The high pressure could either be supplied externally or by evaporation of a part of the pellet. In the latter case, a spark behind the pellet could provide the evaporation and the necessary heating of the driving gas.

Figure 4 shows a fast-acting valve that is able to supply hydrogen gas at high pressure behind a hydrogen pellet held at liquid helium temperature. The valve plate, which is operated mechanically or pneumatically, serves simultaneously as thermal isolation against the cryogenic part of the gun. In principle the construction may allow a sufficiently fast opening time and also be fairly economic from a cryogenic point of view. However, a detailed analysis remains, and a pellet-loader has to be constructed.

Accelerating the pellet in a cylindrical tube with radius r and considering a pellet with a length of $2r$, the pressure driving the pellet, P , the length of the accelerating tube, x , and the final velocity of the pellet, v , are related by the expression:

$$\frac{1}{2} m v^2 = \pi r^2 x P \quad \text{or} \quad \frac{x}{r} = \frac{\rho v^2}{P} . \quad (3)$$

Assuming the maximum pressure to be $5 \times 10^5 \text{ N/m}^2$, and taking a pellet radius of 1 mm, we obtain the following values for the acceleration lengths and times, t , for the two velocities in question

$$\begin{aligned} x_{300} &= 1.6 \text{ cm} & t_{300} &= 0.1 \text{ msec}, \\ x_{10^4} &= 18 \text{ m} & t_{10^4} &= 3.6 \text{ msec}. \end{aligned}$$

If the gas is generated by evaporating the pellet material, the fraction of the pellet that is evaporated is given by,

$$f = \frac{x}{2r} \frac{\rho_{\text{gas}}}{\rho_{\text{solid}}} = \frac{M v^2}{2 \pi T_{\text{gas}}}, \quad (4)$$

where M is the mass of a hydrogen molecule and π is Boltzmann's constant.

Here we have used the ideal gas law, equation 3, and neglected the loss in weight of the pellet.

Choosing the gas temperature arbitrarily, we obtain an estimate of the fraction, f , for the two cases of interest

$$\begin{aligned} v &= 300 \text{ m/s}, & T_{\text{gas}} &= 300 \text{ K}; & f &= 0.04 \\ v &= 10^4 \text{ m/s}, & T_{\text{gas}} &= 10^5 \text{ K}; & f &= 0.12. \end{aligned}$$

It can be seen that it is necessary to assume a very high temperature for the $v = 10^4 \text{ m/s}$ case in order to keep the fraction, f , low. With this choice of gas temperature, we also obtain a pellet velocity smaller than the thermal velocity of the gas. This is important because, if we want to accelerate the pellet to a velocity greater than the thermal velocity, it would be necessary to continuously evaporate from the rear of the pellet in order to obtain a rocket action. This possibility has not been considered.

If the wall of the gun is at liquid helium temperature the driving hydrogen gas will condense on the wall. This can be avoided by pulse heating of the wall to a temperature above the boiling point of hydrogen ($\sim 27.5 \text{ K}$ at $5 \times 10^5 \text{ N/m}^2$). Very likely the heating is also necessary to prevent the pellet from sticking to the wall. Appendix 2 gives an estimate of the fraction, F , of driving gas condensed in a cold acceleration tube. We find that $F_{300} \approx 0.12$ and $F_{10^4} \approx 1$.

It may be possible to accept a driving pressure much larger than indicated by the tensile strength of solid hydrogen, because the pressure of evaporating gas on the sides of the pellet can exert a force counter-balancing the tendency of the pellet to distort.

4. BEESWAX EXPERIMENT

A very simple set-up was made to test the idea and effectiveness of accelerating pellets by means of spark heating and evaporation. Small pellets of beeswax, 1.7 mm in diameter, were shot out of a thin stainless-steel tube. The arrangement is shown in fig. 5. Beeswax was chosen because its melting point is very low, about 60°C, reducing the requirements to the power needed for heating the wall of the tube, and because its plastic properties at room temperature result in a yielding similar to that of hydrogen at liquid helium temperature. The energy delivered to the tube was about 70 J, and the time constant of the current was of the order of 10 msec.

The velocity of the pellet was determined by measuring the delay between the onset of the spark and the time at which a signal was obtained from the earphone (see fig. 5).

A condenser of 0.2 μ F, charged to 5-10 kV, was discharged through a resistance, R, of either 50 or 100 Ω . The delay between the heating pulse and the discharge was 5-10 msec, and the discharge lasted for 50 to 100 μ s. The voltage across the electrodes was measured to be of the order of 50 V and to be fairly independent of the values of the high voltage and resistance. This means that for all cases an energy of approximately 0.1 J was delivered to the spark. The maximum pellet velocities measured were in excess of 100 m/s (see fig. 6 for measurements). The size of the pellets used in the experiment varied, but those with masses of about 12 mg attained velocities of about 75 m/s. This means that a large portion of the energy delivered to the spark appeared as kinetic energy of the pellet (of the order of 33%).

Very little care was taken to optimize the parameters of the experiment; nevertheless, the result seems promising. The mass density of beeswax is roughly ten times that of solid hydrogen indicating that a velocity of 300 m/s might be attainable in the case of a solid hydrogen pellet.

An attempt was made to measure the loss in mass of an accelerated pellet, but it was found negligible (of the order 0.02%). No conclusions can be drawn from this measurement concerning the temperature of the driving gas, since the driving material might originate from the insulator.

5. CONCLUSION

At present no firm conclusion can be drawn about the possibility of accelerating a solid hydrogen pellet up to a velocity of 10^4 m/s. Neither is it possible to present a technically straightforward method to attain an intermediate velocity of 300 m/s. However, pneumatic acceleration seems promising, although the associated cryogenic problems were not treated in great detail. If it proves possible to construct a simple loading system working at 4.2 K, no serious problems should arise.

ACKNOWLEDGEMENT

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APPENDIX 1

A HYDROGEN PELLET SURROUNDED BY A BERYLLIUM SHELL

Let the thin beryllium sphere have radius r and thickness t . The maximum charge will generally be limited by the tensile strength. We wish to compare the maximum velocity achievable through electrostatic acceleration of a plain hydrogen sphere with that of a sphere with a beryllium coating.

For the hydrogen pellet we can express the velocity, v_H , as

$$v_H^2 = \frac{6V\sqrt{2\epsilon_0 S_H}}{\rho_H r}$$

where we use equations 1 and 2. S_H is the maximum stress.

For the beryllium shell, the force is

$$2\pi r t S_{Be} \approx P\pi r^2$$

and this, together with equations 1 and 2, gives the velocity, v_{Be} , for a hydrogen pellet coated with beryllium

$$v_{Be}^2 = \frac{12V}{r\rho_H + 3t\rho_{Be}} \sqrt{\frac{\epsilon_0 t S_{Be}}{r}}$$

The maximum v_{Be}^2 occurs when

$$t = \frac{r\rho_H}{3\rho_{Be}}$$

Now we have

$$\frac{v_{Be, \max}^2}{v_H^2} = \sqrt{\frac{\rho_H S_{Be}}{6\rho_{Be} S_H}}$$

Using $S_H = 5 \cdot 10^5 \text{ N/m}^2$, $S_{Be} \approx 1.3 \cdot 10^8 \text{ N/m}^2$, $\rho_H = 8.8 \text{ kg/m}^3$, and $\rho_{Be} = 1.8 \cdot 10^3 \text{ kg/m}^3$, we find

$$\frac{v_{Be, \max}}{v_H} = 1.5.$$

APPENDIX 2

GAS CONDENSATION IN A COLD ACCELERATION TUBE

To minimize the amount of gas condensation, a material with low thermal conductivity and heat capacity must be chosen. Glass or stainless steel seem reasonable choices. We will assume a glass wall:

$$\text{Thermal conductivity}^{15)}, \quad \kappa \approx 0.1 + 0.1 \frac{T}{25} \frac{\text{W}}{\text{m} \cdot \text{K}}$$

$$\text{Heat capacity}^{16)}, \quad C \approx T \frac{\text{J}}{\text{kg} \cdot \text{K}}$$

$$\text{Density,} \quad \rho_{gl} \approx 2.5 \cdot 10^3 \text{ kg/m}^3.$$

The heat flow equation is

$$\frac{\partial T}{\partial t} = \frac{1}{\rho C} \frac{\partial}{\partial x} \left(\kappa \frac{\partial T}{\partial x} \right).$$

Roughly speaking, the depth of heat penetration Δx in a time Δt will be

$$\Delta x \approx \sqrt{\frac{\Delta t}{\rho_{gl} C}}.$$

and the energy per unit area is

$$\Delta E \approx \Delta x \Delta T \rho_{gl} C \approx \Delta T \sqrt{\rho_{gl} C \kappa \Delta t}.$$

The vaporization heat of H_2 in the range $0 - 10^6 \text{ N/m}^2$ is approximated by

$$\Delta H \approx 5.1 \cdot 10^5 - 0.22 P \text{ (N/m}^2\text{)} \quad \text{J/kg}.$$

The amount of gas condensing per meter of tube length is then

$$\frac{\Delta E}{\Delta H} 2\pi r$$

and the fraction of gas condensing

$$F = \frac{1}{\rho_{gas} \pi r^2 x} \int_0^x \frac{\Delta E}{\Delta H} 2\pi r dz,$$

or, using the gas law,

$$F = \frac{2\pi T_{\text{gas}} \Delta T \sqrt{\rho_{\text{gl}}} C K}{\Delta H M \text{Pr} x} \int_0^x \sqrt{\Delta t} dz$$

and

$$\Delta t = \sqrt{\frac{2x}{g}} - \sqrt{\frac{2z}{g}}.$$

Here z is the distance from the bottom of the acceleration tube, and g is the acceleration of the pellet. Carrying out the integration, we find

$$F = \frac{16\pi T_{\text{gas}} \Delta T \sqrt{\rho_{\text{gl}}} C K t}{15 \Delta H M \text{Pr}}.$$

For the $V = 300 \text{ m/s}$ case we find

$$F_{300} \approx 0.12.$$

Here we use

$$\Delta T = 27.5 - 4.2 \text{ K} = 23.3 \text{ K}$$

and take C and K at 16 K.

Our calculation is no longer valid for the $v = 10^4 \text{ m/s}$ case, but it indicates that a large amount of gas will be condensated at the tube wall, $F_{10^4} \rightarrow 1$.

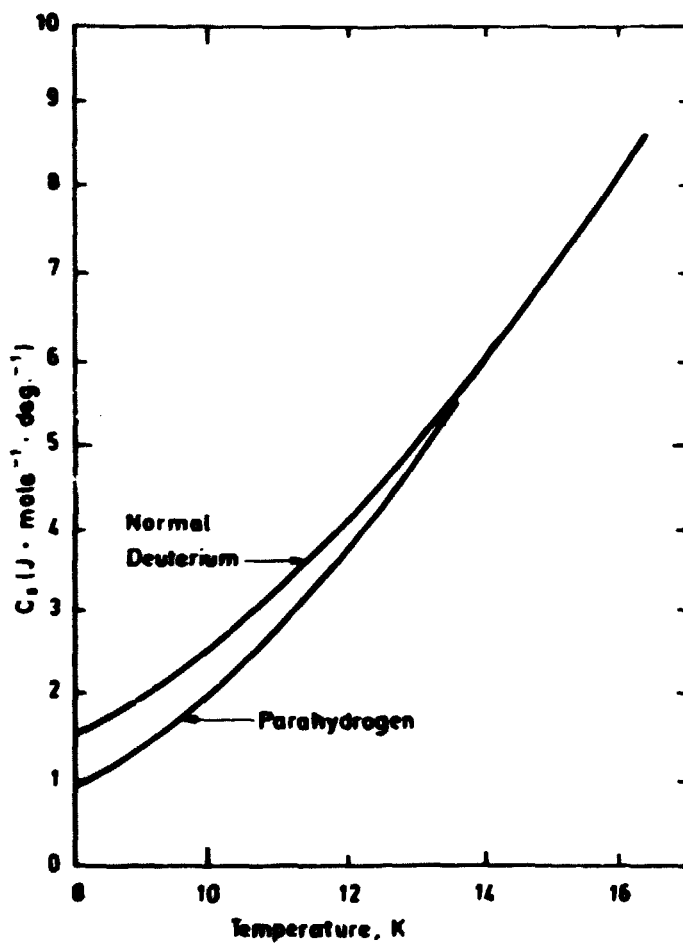


Fig. 1. Heat capacity of parahydrogen and normal deuterium (ref. 9).

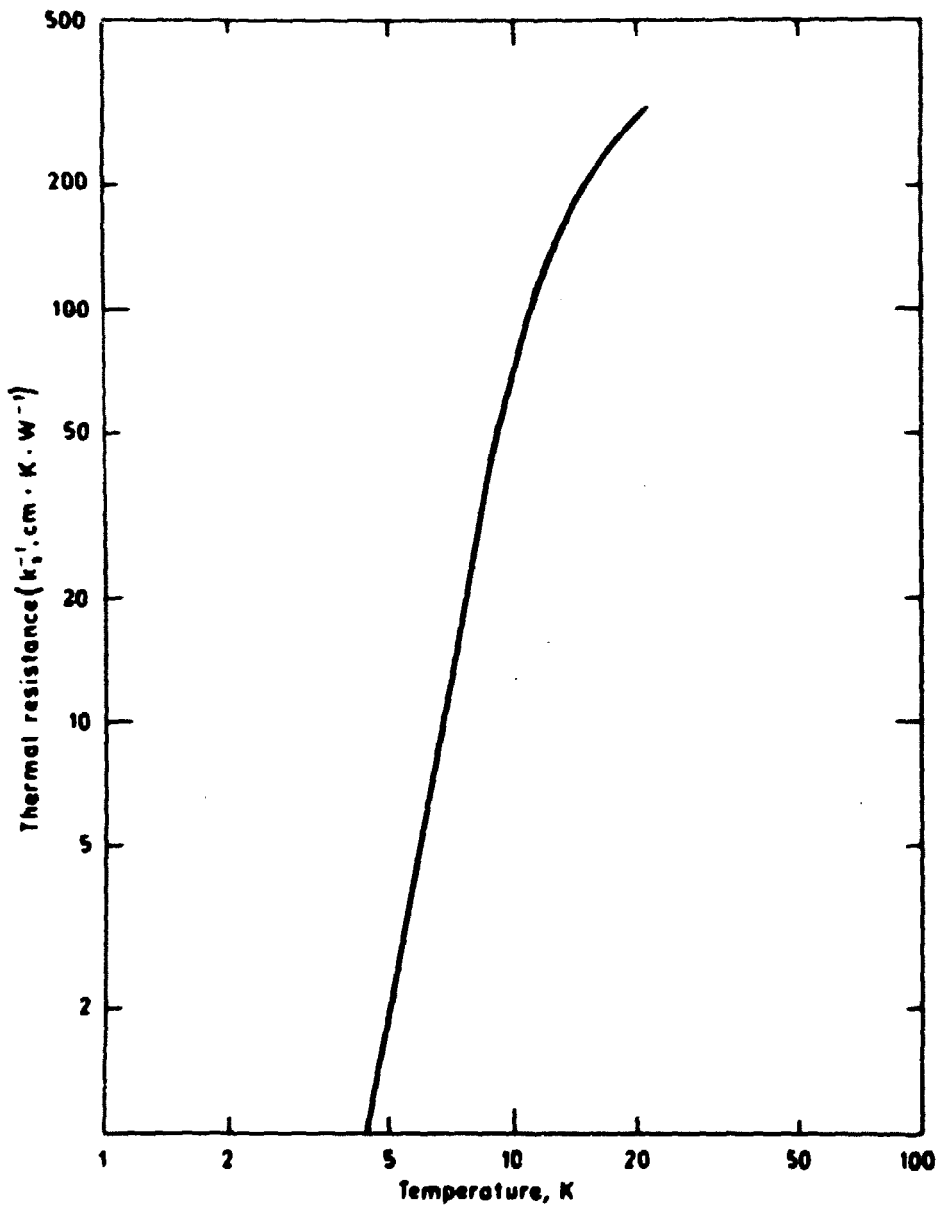


Fig. 2. Thermal resistance of deuterium (ref. 10).

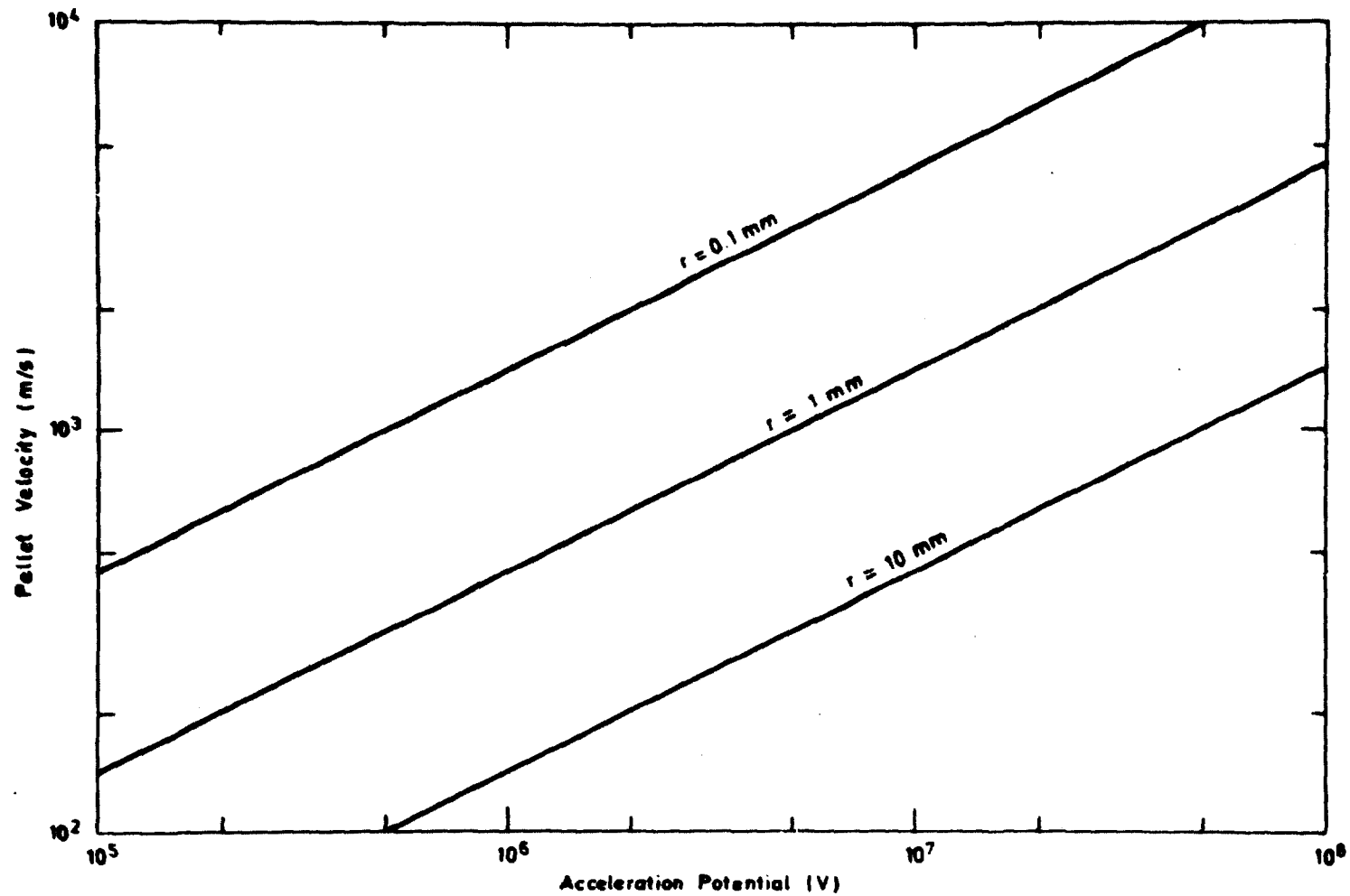
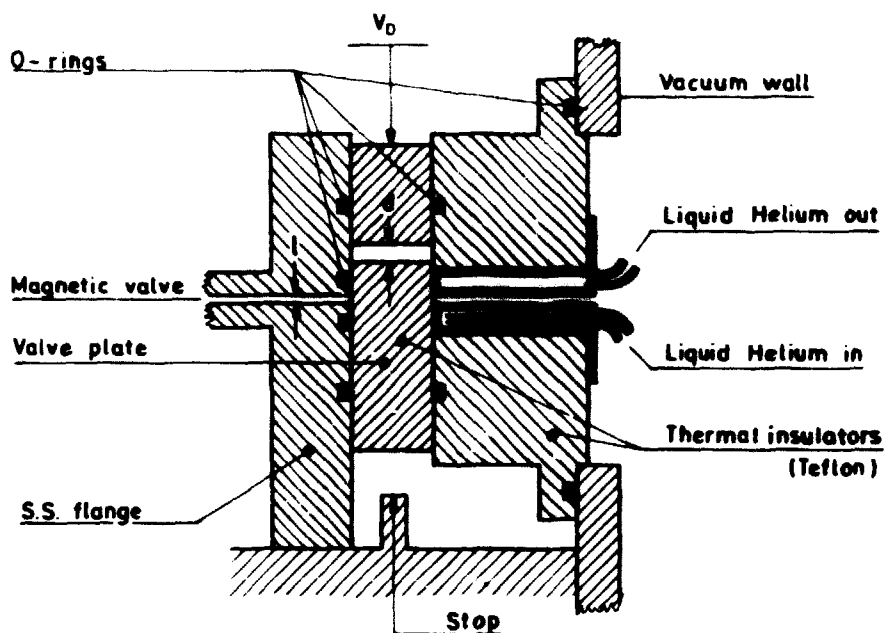


Fig. 3. Velocity of a hydrogen pellet as a function of accelerating voltage for different pellet sizes.



Length of time open: d/V_0

Opening time: l/V_0

Fig. 4. Diagram of fast-acting valve for pneumatic pellet acceleration.

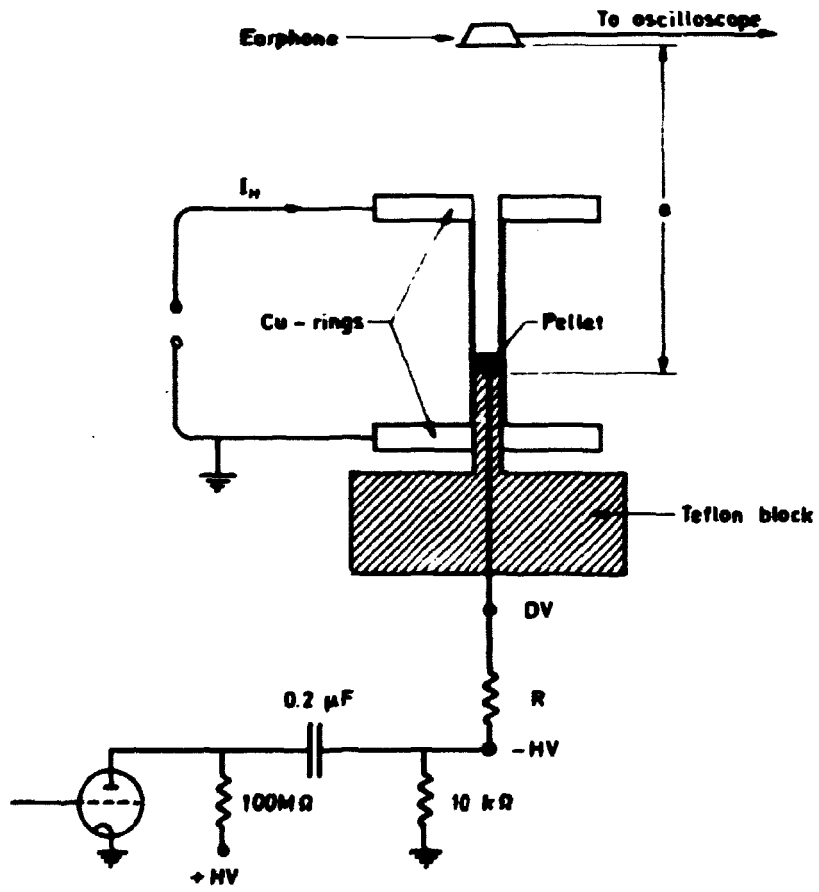


Fig. 5. Diagram of experimental set-up for beeswax experiment.

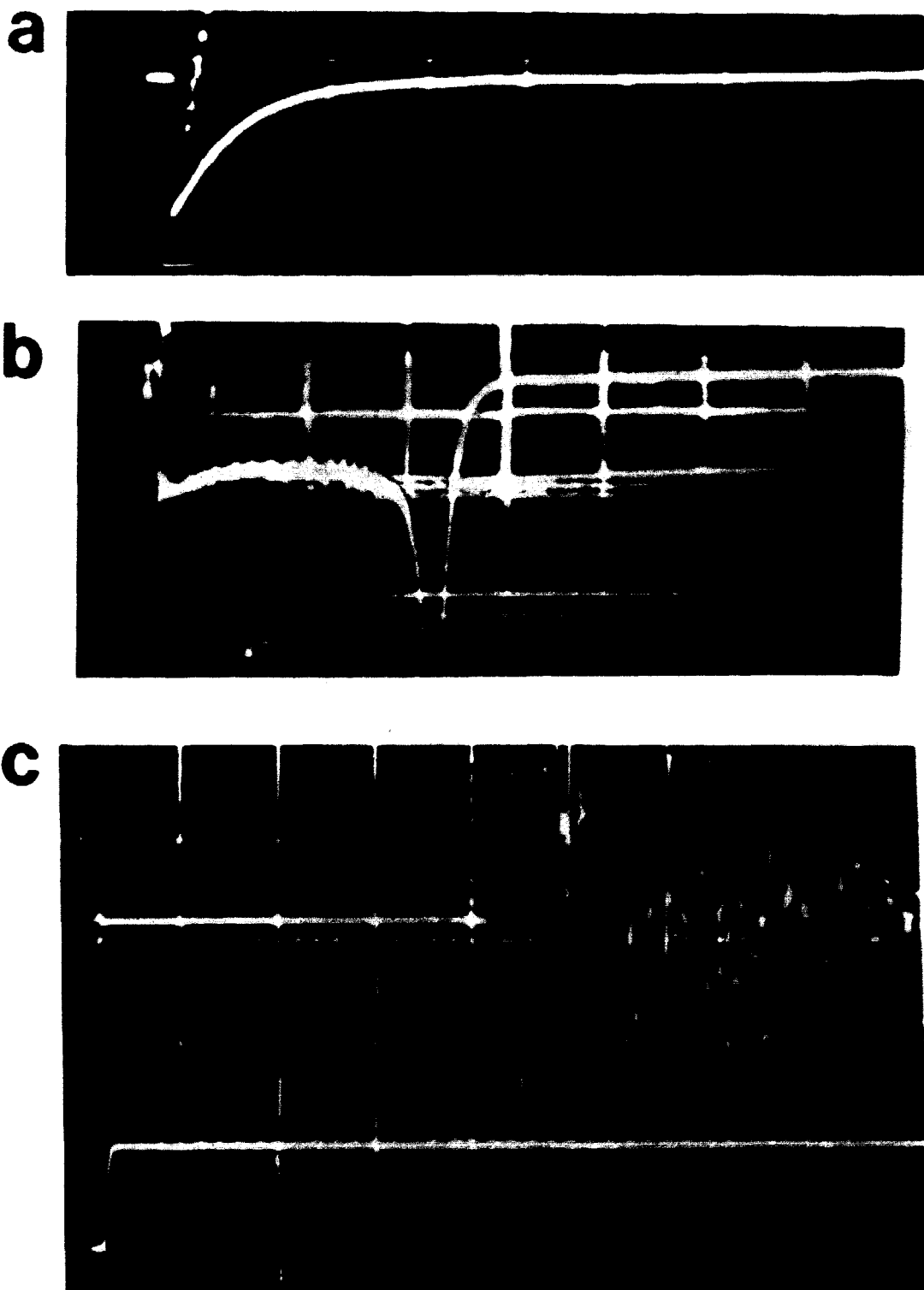


Fig. 6. Measurements from bees wax experiment: a) The voltage-HV (see fig. 5) for $R = 50\%$ and $+HV = 6\text{ kV}$, $20\ \mu\text{s/div}$ abscissa, 5 kV/div ordinate; b) The voltage, DV, across the discharge in the tube (see fig. 5) for $R = 50\%$ and $+HV = 6\text{ kV}$, $20\ \mu\text{s/div}$ abscissa, 50 V/div ordinate; c) Signal from earphone, 1 ms/div (lower trace shows DV).